

# Universal relaxation in quark-gluon plasma at strong coupling

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## Abstract

We use top-down gauge theory/string theory correspondence to compute relaxation rates in strongly coupled nonconformal gauge theory plasma. We compare models with difference mechanisms of breaking the scale invariance: "hard breaking" (by relevant operators) and "soft breaking" (by marginal operators). We find that the thermalization time of the transverse traceless fluctuations of the stress-energy tensor is rather insensitive to the mechanisms of breaking the scale invariance over a large range of the scale-breaking parameter  $\delta = \frac{1}{3} - c_s^2$ . We comment on the relevance of the results to QCD quark-gluon plasma.

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## 1 Introduction

In a recent paper [1] it was pointed out that the equilibration rates in strongly coupled nonconformal quark-gluon plasma (QGP) are surprisingly insensitive to the presence of the conformal symmetry breaking scale. Specifically, considering supersymmetric mass deformations within  $\mathcal{N} = 2^*$  gauge theory and using holography [2, 3] the authors computed the spectra of quasinormal modes for a variety of scalar operators, as well as the energy-momentum tensor. In each case, the lowest quasinormal frequency, which provides an approximate upper bound on the thermalization time, was found to be proportional to temperature, up to a pre-factor with only a mild temperature dependence. Similar results were reported for a conformal plasma with a finite charge density and in the presence of an external magnetic field [4], as well as in a phenomenological nonconformal holographic models [5, 6].

In this paper we continue investigation of the equilibration rates in strongly coupled quark-gluon plasma with holographic string theory dual (the top-down models). One drawback of  $\mathcal{N} = 2^*$  model studied in [1] is the fact that the conformal invariance there is broken quite mildly — over the range of the supersymmetric mass deformation parameter  $\frac{m}{T}$ , the scale invariance is violated by

$$\max_{\frac{m}{T}} \frac{\epsilon - 3p}{\epsilon} \approx 20\% . \quad (1.1)$$

In (1.1)  $\epsilon$  and  $p$  are the energy density and the pressure in  $\mathcal{N} = 2^*$  plasma. On the contrary, the latest results from the HotQCD Collaboration [7] indicate that the analogous quantity in QCD is approximately 50%. Furthermore, it is important to

verify how robust are the results of [1] in theories with a different mechanism for breaking the scale invariance. The ideal model to address these two questions is the Klebanov-Strassler (KS) cascading gauge theory [8]. First, the conformal invariance in KS gauge theory is broken much stronger [9]; second, while the renormalization group (RG) flow in  $\mathcal{N} = 2^*$  gauge theory is induced by relevant operators, the RG flow in KS gauge theory is induced by marginal, but not exactly marginal, operators. We compute the lowest quasinormal mode associated with the transverse traceless fluctuations of the stress-energy tensor in KS gauge theory.

We omit technical details and focus on results only<sup>1</sup>. In the next section we recall definitions of  $\mathcal{N} = 2^*$  gauge theory and KS gauge theory. We compare the thermodynamics of the two models with that of the lattice QCD [7]. In section 3 we present results for the lowest quasinormal mode of the transverse traceless fluctuations of the stress-energy tensor in KS plasma, and compare them with the corresponding computations in [1]. Finally, we conclude in section 4.

## 2 Thermodynamics of strongly coupled nonconformal plasma from holography

The best studied example of the gauge theory/string theory correspondence is that between the maximally supersymmetric  $\mathcal{N} = 4$   $SU(N)$  supersymmetric Yang-Mills theory (SYM) and string theory in  $AdS_5 \times S^5$  [2]. SYM is conformally invariant. At strong coupling, the energy density and the pressure of equilibrium SYM plasma at temperature  $T$  is given by

$$\epsilon = \frac{3}{8}\pi^2 N^2 T^4, \quad p = \frac{1}{8}\pi^2 N^2 T^4. \quad (2.1)$$

In what follows we find it convenient to parameterized thermodynamic potentials of nonconformal plasma with the following conformal symmetry breaking parameters:

$$\Theta \equiv \frac{\epsilon - 3p}{\epsilon}, \quad \delta \equiv \frac{1}{3} - c_s^2, \quad (2.2)$$

where  $c_s$  is the speed of sound waves in plasma. As we see below, parameterization (2.2) allows to compare different holographic models with lattice QCD. Note that from (2.1),

$$\Theta \Big|_{\mathcal{N}=4} = 0, \quad \delta \Big|_{\mathcal{N}=4} = 0. \quad (2.3)$$

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<sup>1</sup>The thermodynamics of KS gauge theory has been studied in [10–16].

$\mathcal{N} = 2^*$  gauge theory is obtained as a mass deformation of  $\mathcal{N} = 4$  SYM, where an  $\mathcal{N} = 2$  hypermultiplet receives a mass  $m$ . This is a *relevant* deformation of the conformal SYM, as the renormalization group flow is induced by bosonic and fermionic mass terms of the hypermultiplet. At large temperatures, *i.e.*,  $\frac{m}{T} \ll 1$ , the thermodynamics of  $\mathcal{N} = 2^*$  gauge theory plasma is given by [17, 18]

$$\begin{aligned}\epsilon &= \frac{3}{8}\pi^2 N^2 T^4 \left( 1 - \frac{2}{3} \frac{\Gamma(3/4)^4}{\pi^4} \frac{m^2}{T^2} + \mathcal{O}\left(\frac{m^4}{T^4} \ln \frac{T}{m}\right) \right), \\ p &= \frac{1}{8}\pi^2 N^2 T^4 \left( 1 - 2 \frac{\Gamma(3/4)^4}{\pi^4} \frac{m^2}{T^2} + \mathcal{O}\left(\frac{m^4}{T^4} \ln \frac{T}{m}\right) \right),\end{aligned}\tag{2.4}$$

resulting in

$$\Theta = 6\delta + \mathcal{O}(\delta^2 \ln \delta).\tag{2.5}$$

Klebanov-Strassler cascading gauge theory is  $\mathcal{N} = 1$  four-dimensional supersymmetric  $SU(K+P) \times SU(K)$  gauge theory with two chiral superfields  $A_1, A_2$  in the  $(K+P, \overline{K})$  representation, and two fields  $B_1, B_2$  in the  $(\overline{K+P}, K)$  representation. Perturbatively, this gauge theory has two gauge couplings  $g_1, g_2$  associated with two gauge group factors, and a quartic superpotential

$$W \sim \text{Tr} (A_i B_j A_k B_\ell) \epsilon^{ik} \epsilon^{j\ell}.\tag{2.6}$$

When  $P = 0$  above theory flows in the infrared to a superconformal fixed point, commonly referred to as Klebanov-Witten (KW) theory [19]. At the IR fixed point KW gauge theory is strongly coupled — the superconformal symmetry together with  $SU(2) \times SU(2) \times U(1)$  global symmetry of the theory implies that anomalous dimensions of chiral superfields  $\gamma(A_i) = \gamma(B_i) = -\frac{1}{4}$ , *i.e.*, non-perturbatively large. Notice that the superpotential (2.6) is *marginal* at the fixed point. When  $P \neq 0$ , conformal invariance of the above  $SU(K+P) \times SU(K)$  gauge theory is broken. It is useful to consider an effective description of this theory at energy scale  $\mu$  with perturbative couplings  $g_i(\mu) \ll 1$ . It is straightforward to evaluate NSVZ beta-functions for the gauge couplings. One finds that while the sum of the gauge couplings does not run

$$\frac{d}{d \ln \mu} \left( \frac{\pi}{g_s} \equiv \frac{4\pi}{g_1^2(\mu)} + \frac{4\pi}{g_2^2(\mu)} \right) = 0,\tag{2.7}$$

the difference between the two couplings is

$$\frac{4\pi}{g_2^2(\mu)} - \frac{4\pi}{g_1^2(\mu)} \sim P [3 + 2(1 - \gamma_{ij})] \ln \frac{\mu}{\Lambda},\tag{2.8}$$

where  $\Lambda$  is the strong coupling scale of the theory and  $\gamma_{ij}$  are anomalous dimensions of operators  $\text{Tr } A_i B_j$ . Given (2.8) and (2.7) it is clear that the effective weakly coupled description of  $SU(K+P) \times SU(K)$  gauge theory can be valid only in a finite-width energy band centered about  $\mu$  scale. Indeed, extending effective description both to the UV and to the IR one necessarily encounters strong coupling in one or the other gauge group factor. As explained in [8], to extend the theory past the strongly coupled region(s) one must perform Seiberg duality [20]. Turns out, in this gauge theory, Seiberg duality transformation is a self-similarity transformation of the effective description so that  $K \rightarrow K - P$  as one flows to the IR, or  $K \rightarrow K + P$  as the energy increases. Thus, extension of the effective  $SU(K+P) \times SU(K)$  description to all energy scales involves and infinite sequence - a *cascade* - of Seiberg dualities where the rank of the gauge group is not constant along RG flow, but changes with energy according to [10]

$$K = K(\mu) \sim 2P^2 \ln \frac{\mu}{\Lambda}, \quad (2.9)$$

at least as  $\mu \gg \Lambda$ . Since [8]

$$\gamma_{ij} = -\frac{1}{2} + \mathcal{O}\left(\frac{P^2}{K^2}\right), \quad (2.10)$$

the superpotential (2.6) is marginal, but *not exactly marginal* at the Klebanov-Witten ultraviolet fixed point of the theory. Although there are infinitely many duality cascade steps in the UV, there is only a finite number of duality transformations as one flows to the IR (from a given scale  $\mu$ ). The space of vacua of a generic cascading gauge theory was studied in details in [21]. In the simplest case, when  $K(\mu)$  is an integer multiple of  $P$ , cascading gauge theory confines in the infrared with a spontaneous breaking of the chiral symmetry  $U(1) \supset \mathbb{Z}_2$  [8]. Here, the full global symmetry of the ground state is  $SU(2) \times SU(2) \times \mathbb{Z}_2$ . At large temperatures, *i.e.*,  $\frac{\Lambda}{T} \ll 1$ , the thermodynamics of KS gauge theory plasma is given by

$$\begin{aligned} \epsilon &= \frac{243}{256} \frac{\Lambda^4}{\pi^4} e^{\frac{2K(T)}{P^2}} \left( 1 + \frac{P^2}{3K(T)} + \mathcal{O}\left(\frac{P^4}{K(T)^2}\right) \right), \\ p &= \frac{81}{256} \frac{\Lambda^4}{\pi^4} e^{\frac{2K(T)}{P^2}} \left( 1 - \frac{P^2}{K(T)} + \mathcal{O}\left(\frac{P^4}{K(T)^2}\right) \right), \end{aligned} \quad (2.11)$$

with

$$\frac{dK(T)}{d \ln \frac{T}{\Lambda}} = 2P^2 \left( 1 + \mathcal{O}\left(\frac{P^2}{K(T)}\right) \right), \quad (2.12)$$

resulting in

$$\Theta = 3\delta + \mathcal{O}(\delta^2). \quad (2.13)$$

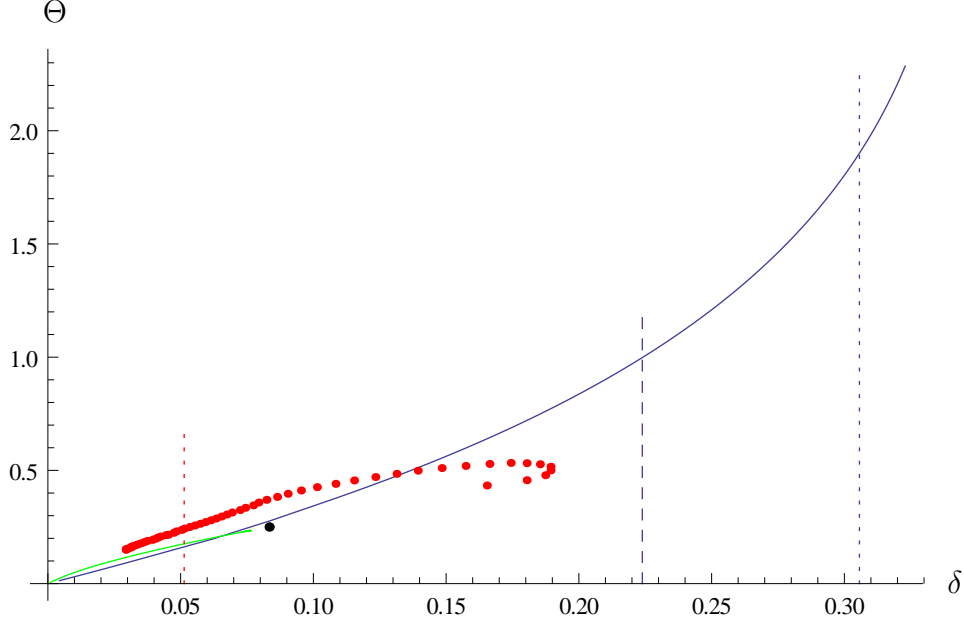


Figure 1: Parameterization of  $\Theta = \frac{\epsilon - 3p}{\epsilon}$  with  $\delta = \frac{1}{3} - c_s^2$  in strongly coupled gauge theory plasma for QCD (the red dots),  $\mathcal{N} = 2^*$  (the solid green line), and cascading gauge theory (the solid blue line). The dashed red line represents the conformal violation parameter  $\delta$  in QCD at  $T = 0.3\text{GeV}$ . The black dot is the  $\frac{m}{T} \rightarrow 0$  limit of  $\mathcal{N} = 2^*$  thermodynamics. Vertical blue lines represent the phase transitions in cascading gauge theory plasma: the confinement/deconfinement (dashed) and the chiral symmetry breaking (dotted).

Using results of Table I of [7] we can reconstruct  $\Theta$ -vs- $\delta$  for QCD. These results are presented by red dots in figure 1. The dashed vertical red line represents QCD nonconformality parameter  $\delta$  at temperature of<sup>2</sup>  $0.3\text{GeV}$ . QCD data points at temperatures higher than  $0.3\text{GeV}$  correspond to weaker breaking of conformal invariance — they are to the left of the dashed red line. The solid green line parameterizes  $\mathcal{N} = 2^*$  thermodynamics [22]. In the deep infrared, *i.e.*,  $\frac{m}{T} \rightarrow 0$ ,  $\mathcal{N} = 2^*$  thermodynamics reduces to that of the five-dimensional CFT [23, 24]. The latter limit is represented by a black dot,

$$\left. \{\delta, \Theta\} \right|_{\text{black dot}} = \left\{ \frac{1}{12}, \frac{1}{4} \right\}. \quad (2.14)$$

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<sup>2</sup>We choose this as a characteristic temperature for initializing hydrodynamic codes to model RHIC collisions.

The solid blue line parameterizes the thermodynamics of cascading gauge theory plasma [14, 16]. The vertical blue dashed and dotted lines represent the nonconformality parameter  $\delta$  of KS gauge theory at the first-order confinement/deconfinement transition,

$$T_{\text{deconfinement}} = 0.6141111(3)\Lambda, \quad \delta_{\text{deconfinement}} = 0.2238(9), \quad (2.15)$$

and the (perturbative) chiral symmetry breaking phase transition,

$$T_{\chi s B} = 0.8749(0)T_{\text{deconfinement}}, \quad \delta_{\chi s B} = 0.30567(2), \quad (2.16)$$

correspondingly. Notice that while conformal invariance of cascading gauge theory plasma can be broken much more strongly (especially in the vicinity of the phase transitions) compare to that of  $\mathcal{N} = 2^*$  plasma, the results are of little relevance to QCD QGP — in fact, for QCD temperatures  $T \gtrsim 0.3\text{GeV}$  both  $\mathcal{N} = 2^*$  and KS plasma have very similar equations of state, the latter are further quite reasonable compared with lattice QCD.

### 3 Relaxation in strongly coupled nonconformal plasma from holography

We now study the effects of conformal symmetry breaking on the thermalization time in strongly coupled gauge theory plasma comparing top-down holographic models:  $\mathcal{N} = 2^*$  and KS gauge theory plasma. We focus on relaxation of the transverse traceless fluctuations of the stress-energy tensor. In the holographic dual they are encoded as quasinormal modes of helicity-2 graviton polarizations [25]. These fluctuations are always equivalent to fluctuations of a minimally coupled massless scalar [26].

In figure 2 we plot the minus imaginary part of the lowest quasinormal modes at zero spatial momentum of the transverse traceless fluctuations on the stress-energy tensor in  $\mathcal{N} = 2^*$  (the solid green line) [1] and cascading (the solid blue line) gauge theory plasma as a function of the conformal symmetry breaking parameter  $\delta = \frac{1}{3} - c_s^2$ . In  $\mathcal{N} = 2^*$  gauge theory plasma  $\delta \in [0, \frac{1}{12}]$  with the upper limit denoted by the black dot, representing the imaginary part of the lowest quasinormal mode of dimension  $\Delta = 5$  operator in the effective five-dimensional CFT in the IR:

$$\left\{ \delta, -\text{Im} \frac{\omega}{2\pi T} \right\} \Big|_{\text{black dot}} = \left\{ \frac{1}{12}, 1.07735(7) \right\}. \quad (3.1)$$

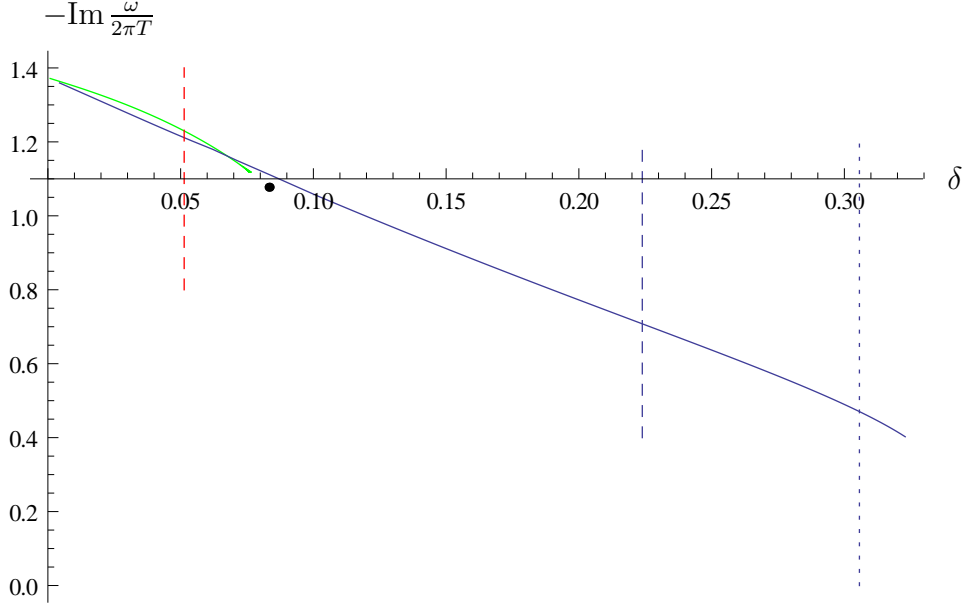


Figure 2: Minus imaginary part of the lowest quasinormal mode at zero spatial momentum of the transverse traceless fluctuations of the stress-energy tensor in  $\mathcal{N} = 2^*$  (the solid green line) and KS (the solid blue line) gauge theory plasma as a function of  $\delta = \frac{1}{3} - c_s^2$ . The black dot denotes the lowest quasinormal mode of dimension  $\Delta = 5$  operator of the effective five-dimensional CFT in the deep IR of  $\mathcal{N} = 2^*$  plasma, see (3.1). The dashed red line represents the conformal violation parameter  $\delta$  in QCD at  $T = 0.3\text{GeV}$ . Vertical blue lines represent the phase transitions in cascading gauge theory plasma: the confinement/deconfinement (dashed) and the chiral symmetry breaking (dotted).

Notice that over all the parameter range of  $\delta$  of  $\mathcal{N} = 2^*$  the relaxation rates of  $\mathcal{N} = 2^*$  gauge theory and KS gauge theory are practically identical. This is the basis of the universality observation for the relaxation rates in strongly coupled nonconformal gauge theory plasma with a dual holographic description.

In [1] it was found that momentum dependence of the relaxation rates is rather weak in strongly coupled gauge theory plasma with a holographic dual. We confirm that observation here comparing the momentum dependence of the lowest quasinormal mode of the transverse traceless fluctuations of the stress-energy tensor in KS plasma for three value of  $\delta$ :  $\delta = 0$  (the UV conformal fixed point) (solid lines),  $\delta = \delta_{\text{deconfinement}}$  (dashed lines), and  $\delta = \delta_{\chi s B}$  (dotted lines), see (2.15) and (2.16). In figure 3 we plot



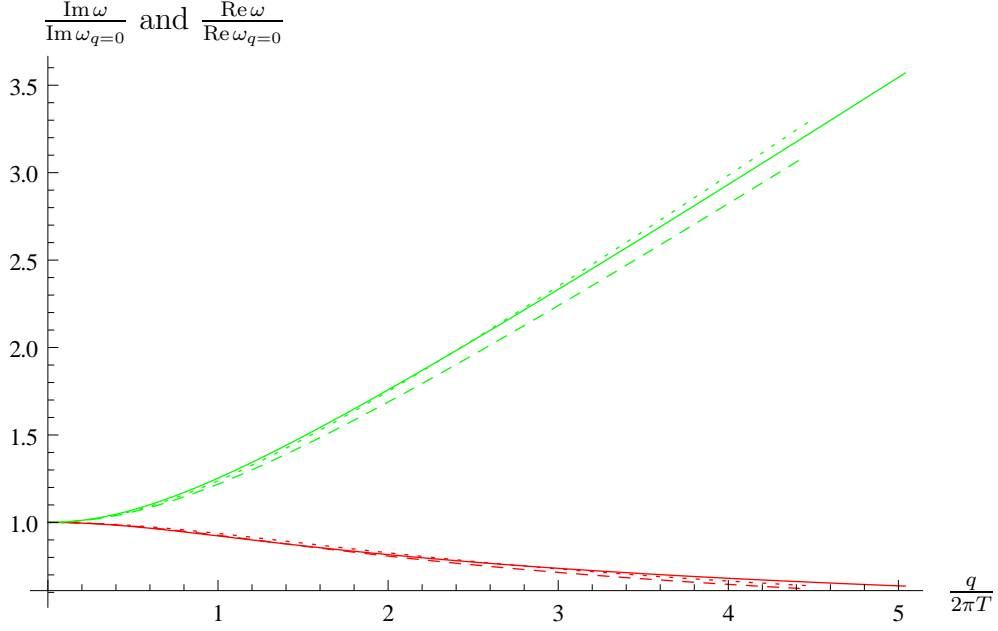


Figure 3: Momentum dependence of the lowest quasinormal mode of the transverse traceless fluctuations of the stress-energy tensor in cascading gauge theory plasma at the ultraviolet fixed point (solid lines), the deconfinement phase transition (dashed lines), and the chiral symmetry breaking phase transition (dotted lines). The green/red lines represent the real/minus imaginary parts of the frequencies. The data is normalized to zero momentum values of the frequencies, see (3.2).

real (green) and minus imaginary (red) parts of the quasinormal frequencies, reduced to their zero momentum values:

$$\begin{aligned}
 \omega_{q=0}^{\delta=0} &= 1.5597(3) - i \, 1.3733(4) , \\
 \omega_{q=0}^{\delta=\delta_{\text{deconfinement}}} &= 1.5825(8) - i \, 0.70783(5) , \\
 \omega_{q=0}^{\delta=\delta_{\chi^{sB}}} &= 1.46632 - i \, 0.47044(1) .
 \end{aligned}
 \tag{3.2}$$

## 4 Conclusion

Relaxation rates in strongly coupled gauge theory plasma are encoded in the lowest quasinormal modes of matter-gravity fluctuations in the corresponding holographic dual. We studied the dependence of the relaxation rates on the mechanism of breaking the conformal invariance in top-down holographic models. Specifically, we compared  $\mathcal{N} = 2^*$  gauge theory rates [1] with those of cascading gauge theory. In the former, the

conformal invariance is broken by relevant operators, while in the latter it is broken by marginal (but not exactly marginal) operators. Remarkably, at least for the relaxation of transverse traceless fluctuations of the stress-energy tensor, the rates are very close. Additionally, we found very weak momentum dependence of the quasinormal mode frequencies. All these provide further support for the universality of the relaxation rates in strongly coupled gauge theories with holographic duals observed in [1, 4–6].

It is important to emphasize that not all relaxation rates in cascading gauge theory plasma are roughly proportional to the temperature. For example, in the vicinity of the chiral symmetry breaking phase transition, the symmetry breaking fluctuations destabilize the system [16] with the corresponding relaxation rate vanishing precisely at the transition point. We believe that this subtlety is of little consequence to QCD applications though, as conformal invariance there is broken much more strongly than in QGP produced at RHIC and LHC (see figure 1).

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